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Lithium-6 from Solar Flares

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ABSTRACT

By introducing a hitherto ignored ^{6}Li producing process, due to accelerated ^{3}He reactions with ^{4}He, we show that accelerated particle interactions in solar flares produce much more ^{6}Li than ^{7}Li. By normalizing our calculations to gamma-ray data we demonstrate that the ^{6}Li produced in solar flares, combined with photospheric ^{7}Li, can account for the recently determined solar wind lithium isotopic ratio, obtained from measurements in lunar soil, provided that the bulk of the flare produced lithium is evacuated by the solar wind. Further research in this area could provide unique information on a variety of problems, including solar atmospheric transport and mixing, solar convection and the lithium depletion issue, and solar wind and solar particle acceleration.

Subject headings: Sun: abundances — Sun: flares — Sun: solar wind — Nuclear Reactions, Nucleosynthsis, Abundances

1. Introduction

The solar wind lithium isotopic ratio, $(^6\mathrm{Li}/^7\mathrm{Li})_{\mathrm{sw}}$ =0.032±0.004, has recently been determined from measurements in lunar soil (Chaussidon & Robert 1999). As these authors point out, this value greatly exceeds the expected photospheric ratio, based on the fact that ^{7}Li in the photosphere is depleted by over a factor of 100 relative to its protosolar value (i.e. the photospheric vs. the meteoritic abundance, Grevesse, Noels, & Sauval 1996), and that this depletion, due to burning at the bottom of the convection zone (Brun, Turck-Chieze, & Zahn 1999), should lead to a much more severe depletion of ^{6}Li, which burns at a lower temperature than ^{7}Li. In addition, there exist observational upper limits on the photospheric ratio, $(^6\mathrm{Li}/^7\mathrm{Li})_{\mathrm{ph}}\leq 0.01$ (Müller, Peytremann, & de la Reza 1975) and $(^6\mathrm{Li}/^7\mathrm{Li})_{\mathrm{ph}}\leq 0.03$ (Ritzenhoff, Schröter, & Schmidt 1997). Chaussidon & Robert (1999) thus suggest that the measured solar wind ^{6}Li must be solar flare produced. However, they only consider ^{6}Li production by spallation from C, N and O. The demonstration that solar flares can indeed account for the ^{6}Li in the solar wind has very important implications on many problems in solar physics.

Light element production by accelerated particle interactions was treated in detail (e.g. Ramaty et al. 1997). In non-solar settings, and for accelerated particles of predominantly low energy, the dominant reactions are ^{4}He(α,p)^{7}Li, ^{4}He(α,n)^{7}Be (with ^{7}Be decaying to ^{7}Li) and ^{4}He(α,x)^{6}Li (where x stands for either a proton and a neutron, or a deuteron). In solar flares, however, the reaction ^{4}He(^{3}He,p)^{6}Li is also very important (Mandzhavidze, Ramaty, & Kozlovsky 1997a), both because of its very low threshold energy and because for solar energetic particles ^{3}He/^{4}He can be as large as 1 or even larger (e.g. Reames 1998). Such ^{3}He/^{4}He enhancements are one of the main characteristics of the acceleration mechanism responsible for impulsive solar energetic particle events, as distinguished from gradual events, based on the duration of the accompanying soft X-ray emission. The ^{3}He enrichment is thought to be due to stochastic acceleration through gyroresonant wave particle interactions which preferentially accelerate the ^{3}He (Temerin & Roth 1992; Miller & Viñas 1993). Concerning the particles which interact at the Sun, evidence for accelerated ^{3}He enrichment was obtained from the detection (Share & Murphy 1998) of a gamma-ray line at 0.937 MeV produced by the reaction ^{16}O(^{3}He,p)^{18}F* (Mandzhavidze, Ramaty, & Kozlovsky 1997b; 1999). Using gamma-ray data from 20 flares, Mandzhavidze et al. (1999) showed that for essentially all of these flares ^{3}He/^{4}He can be as large as 0.1, while for some of them values as high as 1 are possible. In addition, they showed that for the particles that interact and produce gamma rays, ^{3}He enrichments are present for both impulsive and gradual flares. Thus, we can expect $^3\mathrm{He}/^4\mathrm{He} \gtrsim 0.1$ for most flares that produce gamma rays and isotopes at the Sun.

In the present Letter we carry out new calculations of Li production and re-calculate (see Ramaty & Simnett 1991) the average accelerated ion irradiation of the Sun, to show that flare accelerated particle interactions produce enough ^{6}Li which, combined with photospheric ^{7}Li, can account for the solar wind ^{6}Li/^{7}Li measured in lunar soil.

2. Li Production

We employ the nuclear code described in detail in Ramaty et al. (1997) which includes, in addition to the $\alpha\alpha$ reactions mentioned above, also Li production from C, N and O. The cross section for the additional reaction, ^{4}He(^{3}He,p)^{6}Li, is shown in Figure 1, together with the cross sections for the $\alpha\alpha$ reactions producing ^{6}Li and ^{7}Li. For the ^{3}He induced reaction we obtained the cross section for ^{6}Li production in the ground state, from threshold (2.34 MeV/nucleon) to 8.2 MeV/nucleon, by detailed balance using the cross section for the inverse exothermic reaction ^{6}Li(p,^{3}He)^{4}He (Angulo et al. 1999). We added the contribution of the reaction for producing ^{6}Li in the 3.56 MeV excited state which decays to the ground state by photon emission, using data from Harrison (1967). The total cross section at 9.3 MeV/nucleon is from Koepke and Brown (1977), and at 18 and 20.4 MeV/nucleon from Halbert, van der Woude, & O'Fallon (1973). At higher energies we extrapolated the cross section as expected for reactions with 2 particles in the exit channel.

Gamma-ray production in solar flares results predominantly from thick target interactions, meaning that particles accelerated in the upper portions of coronal loops produce nuclear reactions as they slow down in the denser chromospheric region of the loops (e.g. Ramaty & Murphy 1987). We adopt the same model for Li production. The upper panel in Figure 2 shows the resultant thick target ^{6}Li yields, normalized to unit incident total number of protons of energy greater than 30 MeV, $N_{\rm p}(>30)=1$. The energy spectra of the accelerated particles are power laws in kinetic energy per nucleon, with spectral index s (Ramaty, Mandzhavidze, & Kozlovsky 1996). The evidence for enhanced ^{3}He/^{4}He was mentioned above. There is also evidence that α/p could exceed the canonical 0.1, with possible value around 0.5 (Share & Murphy 1997; Mandzhavidze et al. 1999). Thus in Figure 2 we show results for $\alpha/{\rm p} = 0.1$ and 0.5, and ^{3}He/^{4}He=0, 0.1 and 1. We see in the upper panel that the ^{3}He enrichment very significantly increases the lithium production, especially for steep spectra. That the lithium production is mainly due to α particles and ^{3}He nuclei can be seen by comparing the six upper curves with the lowest one, for which we set the α particle and ^{3}He abundances to zero, so that all the ^{6}Li in this case is produced in C, N and O interactions. Considering the flare produced isotopic ratios in the lower panel, we see that while in the absence of ^{3}He, ^{6}Li/^{7}Li is at most unity, much larger ratios are possible with enhanced ^{3}He/^{4}He.

3. Average Solar Proton Irradiation

To calculate the average flare produced lithium, we estimate the average proton irradiation of the Sun, $\dot{N}_{\rm p}(>30{\rm MeV})$ measured in protons per second, where the average is taken over a solar cycle. We follow the method described by Ramaty & Simnett (1991). We start with the flare size distribution measured in 0.3 to 1 MeV bremsstrahlung because observations in this energy range give the most complete sample of solar flare gamma-ray emission (see Vestrand et al. 1999). To minimize the effects of anisotropic electrons (e.g. Miller & Ramaty 1989) we employ the distribution derived for flares near the solar limb (Dermer 1987). For flares at heliocentric longitudes 60° to 90°, observed from March 1980 to February 1986 (approximately half a solar cycle) the size distribution, measured in number of flares per unit $F_{\rm B}$, can be approximated by $dn/dF_{\rm B} \simeq 8.5F_{\rm B}^{-1.1}$, where $10 \lesssim F_{\rm B} \lesssim 6500$ photons cm^{-2} is the observed 0.3 to 1 MeV bremsstrahlung fluence at Earth per flare . The total number of >0.3 MeV emitting flares per solar cycle is obtained by integrating the above expression multiplied by a factor of 12, where a factor of 6 takes into account the whole solar surface and a factor of 2 the other half of solar cycle. We thus obtain 375 flares, which compares well with the 175 flares listed by Vestrand et al. (1999) from which >0.3 MeV bremsstrahlung was observed with the Solar Maximum Mission (SMM) over almost a whole solar cycle. This latter number should be corrected for anisotropy effects, and must be multiplied by a factor of 2 since SMM only observes half the solar surface. The required average irradiation is then given by

$$\dot{N}_{\rm p}(>30) = \frac{12}{T}\int_{10}^{6500} dF_{\rm B}\frac{dn}{dF_{\rm B}}N_{\rm p}(F_{\rm B}) \ , \tag{1}$$

where T is the number of seconds in 11 years and $N_{\rm p}(F_{\rm B})$ is the number of protons above 30 MeV expressed as a function of $F_{\rm B}$. To derive this relationship, we first employ the result of Murphy et al. (1990) that for flares near the limb $F_{\rm B}/F_{\rm N} \simeq 4.5$, where $F_{\rm N}$ is the total nuclear deexcitation line emission fluence observed at Earth. Next we use the nuclear deexcitation code (e.g. Ramaty et al. 1996) to derive $N_{\rm P}(>30)/F_{\rm N}$. This ratio depends on the spectrum and composition of the accelerated particles, in particular α/p. Ramaty et al. (1996) have derived the distribution of power law spectral indexes from gamma-ray data, showing that for a sample of 19 flares the mean $s \simeq 4$. For this value of s we find that $N_{\rm p}(>30)/F_{\rm N} = 1.7\times10^{29}$ and 6.6×10^{29} protons/(nuclear deexcitation photons cm^{-2}), for α/p=0.5 and 0.1, respectively. By using $F_{\rm B}/F_{\rm N}$=4.5 and these $N_{\rm p}(>30)/F_{\rm N}$ to derive $N_{\rm p}(F_{\rm B})$, equation 1 yields $\dot{N}_{\rm p}(>30{\rm MeV})=3.5\times10^{25}$ and 1.4×10^{26} protons s^{-1}, for α/p=0.5 and 0.1, respectively.

4. The Solar Wind ^{6}Li/^{7}Li

Even though a detailed treatment of the time dependent evolution of Li in the solar atmosphere is beyond the scope of this paper, we now show that ^{6}Li production in solar flares could indeed account for the solar wind ^{6}Li/^{7}Li. To demonstrate this we assume the following: (i) all the flare produced ^{6}Li is evacuated by the solar wind, (ii) the photospheric ^{6}Li that is the remnant of its protosolar abundance is negligible, and (iii) the solar wind $(^7{\rm Li/H})_{\rm sw}$ is equal to the photospheric value $(^7{\rm Li/H})_{\rm ph}=1.4\times10^{-11}$ (Grevesse et al. 1996). The solar wind $(^6{\rm Li}/^7{\rm Li})_{\rm sw}$ is then given by

$$\left(\frac{^6{\rm Li}}{^7{\rm Li}}\right)_{\rm sw} = \frac{\dot{N}_{\rm p}(>30)Q(^6{\rm Li})/\dot{F}_{\rm sw}}{(^7{\rm Li/H})_{\rm ph}} \ , \tag{2}$$

where $Q(^6{\rm Li})$ is plotted in Figure 2 and $\dot{F}_{\rm sw}\simeq6\times10^{35}$ s^{-1} is the average solar wind proton flux (Dupree 1996). Taking $s = 4$, $0.1<\alpha/{\rm p}<0.5$ and $0.1<{^3{\rm He}}/{^4{\rm He}}<1$, we obtain $0.007<(^6{\rm Li}/^7{\rm Li})_{\rm sw}<0.06$. This range is consistent with the observed value of 0.032±0.004. Several effects could lead to lower or higher calculated $(^6{\rm Li}/^7{\rm Li})_{\rm sw}$. Clearly there are uncertainties in our estimate of $\dot{N}_{\rm p}(>30$ MeV), in particular there could be a large number of smaller gamma-ray flares, which have not yet been observed, and if they had steep ion energy spectra and high ^{3}He/^{4}He they would contribute significantly to ^{6}Li production. On the other hand, some of the flare-produced ^{6}Li could be mixed downward to the photosphere and lost from the solar wind. The calculated (^{6}Li/^{7}Li)$_{\rm sw}$ would also be lower if (^{7}Li/H)$_{\rm sw}$ were higher than (^{7}Li/H)$_{\rm ph}$, a possibility since Li has low first ionization potential, a factor that biases coronal abundances relative to those of the photosphere (e.g. Reames 1998). Nevertheless, the better than order of magnitude agreement between the calculated and measured (^{6}Li/^{7}Li)$_{\rm sw}$ provides good support to the possibility that the measured ^{6}Li in lunar soil is indeed solar flare produced.

It is of some interest to compare the average ^{6}Li production, $6\times10^{22}<[\dot{N}_{\rm p}(>30)Q(^6{\rm Li})]<5\times10^{23}$ atoms s^{-1}, with the contribution of the 19 large SMM flares from which gamma-ray line emission was observed. Using the method detailed in Mandzhavidze et al. (1999), for each flare we derive s and $N_{\rm p}(>30)$. Then using $Q(^6{\rm Li})$ from Figure 2, taking into account that for 5 of the 19 flares $\alpha/{\rm p}\simeq0.5$ (Mandzhavidze et al. 1999), we obtain the flare-by-flare ^{6}Li productions which yield averages over the 9 year SMM observing period of 1×10^{22} and 7×10^{22} ^{6}Li atoms s^{-1}, if for all flares ^{3}He/^{4}He=0.1 and 1, respectively. Thus, about 15% of the ^{6}Li production that we derived using the flare size distribution could result from 19 of the largest flares. Concerning the contributions of individual flares, as much as a few times 10^{30} Li atoms could be produced by a large flare and most of these would be ^{6}Li (Mandzhavidze et al. 1997a)

5. Discussion and Conclusions

We demonstrated that it is possible to produce enough ^{6}Li by flare accelerated particles to account for the measured ^{6}Li/^{7}Li in lunar soil that is thought to originate from solar wind implantation. The presence of enriched accelerated particle ^{3}He is essential for the production of sufficient ^{6}Li. We note that the radioactive ^{26}Al in the early solar system is thought to be produced in ^{3}He induced reactions (Lee et al. 1998). This raises the possibility that some of the meteoritic ^{6}Li could also be of local early solar system origin.

Kotov et al. (1996) claimed that flare accelerated particle interactions could account for all the photospheric lithium. If this were true, since the solar wind acceleration is not expected to significantly alter the lithium isotopic ratio, the solar wind ^{6}Li/^{7}Li should exceed 0.2 (Figure 2), contrary to the observed value of 0.03. This confirms the previous result of Mandzhavidze et al. (1997a) that production in flares does not make a significant contribution to the average photospheric lithium. But the fact that as much as 10^{30} Li atoms are produced in large solar flares, suggests that flare produced lithium may be detected in a small area of the solar surface near the foot points of the flaring loops shortly after the time of the flare (see Livshits 1997). In this connection, it is interesting to point out that Ritzenhoff et al. (1997) don't rule out the presence of ^{6}Li near a sunspot at a value close to their reported upper limit ^{6}Li/^{7}Li$\leq$0.03, which in fact coincides with the measured solar wind value.

Further research in this area requires direct measurement of lithium and its isotopic ratio in the solar wind, spectroscopic measurements of ^{6}Li in the photosphere, and the detection of gamma rays from small flares that would lead to a more precise determination of the proton irradiation of the Sun. All of these should lead to new insights into the processes of transport and mixing in the solar atmosphere and of the acceleration of the solar wind.

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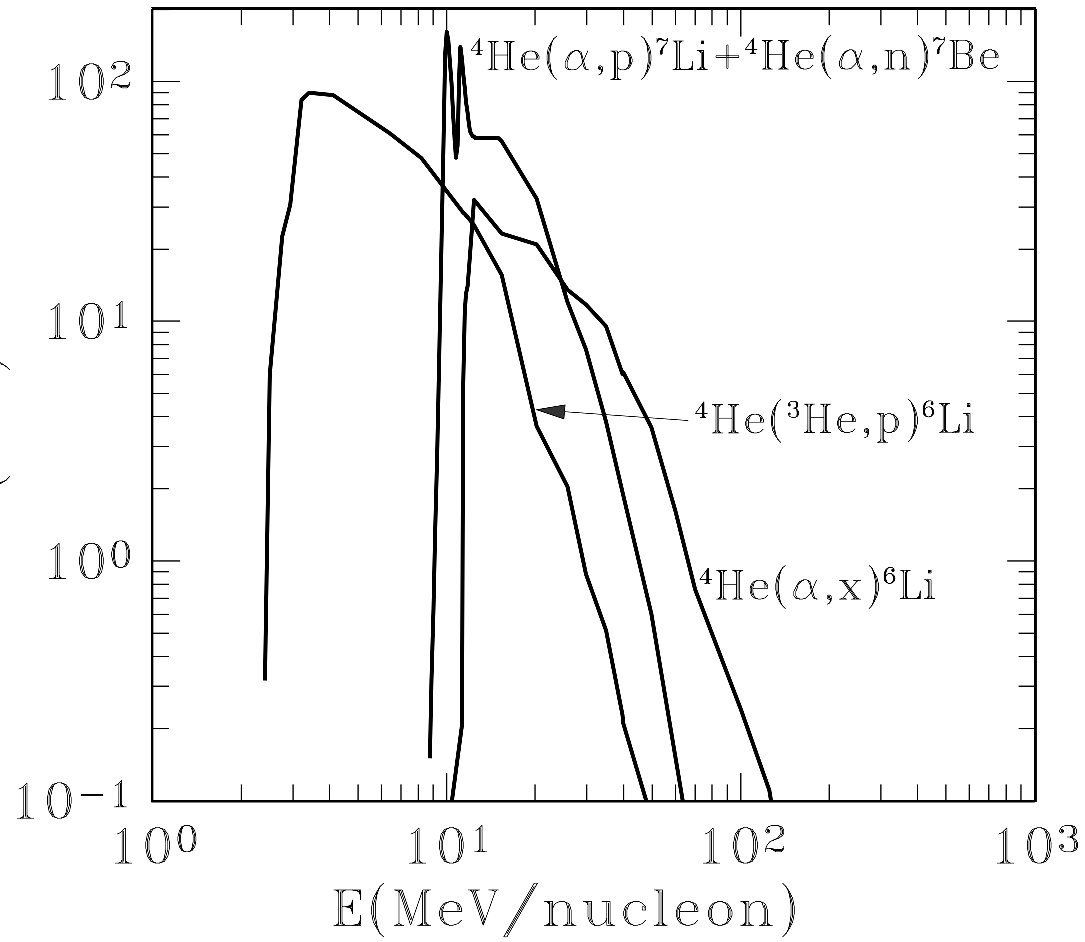

Fig. 1.— ^{6}Li production cross sections in accelerated ^{3}He and α particle interactions with He.

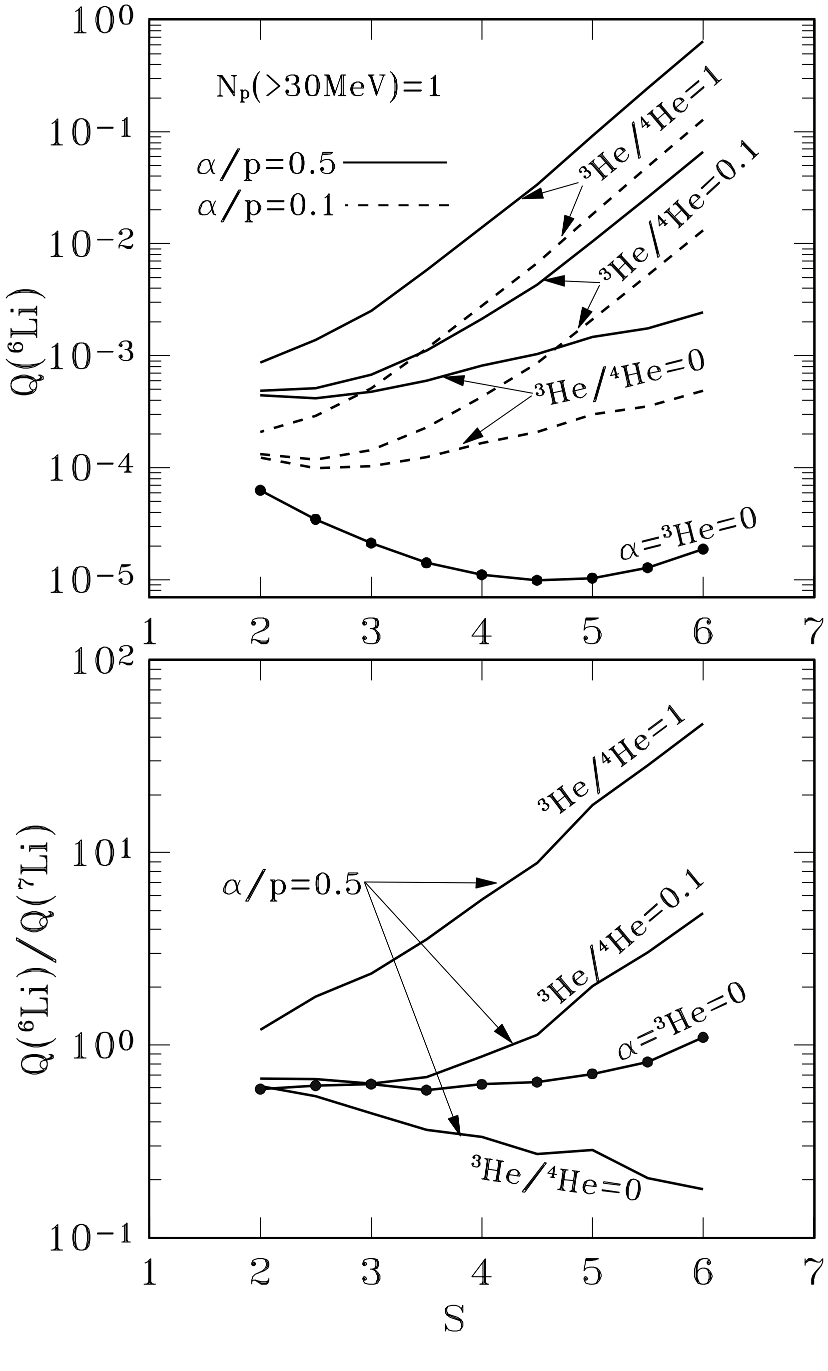

Fig. 2.— Upper panel: Thick target ^{6}Li productions by accelerated particles with power law in kinetic energy per nucleon spectra with spectral index s and normalized to 1 proton of energy greater than 30 MeV. For the curve with α=^{3}He=0, the production is due solely to CNO interactions. Lower panel: Isotopic ratios; for α/p=0.1 (not shown) the values are practically identical to those shown for α/p=0.5.